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AN AUTOMATIC BALANCING SYSTEM FOR USE ON FRICTIONLESSLY SUPPORTED ATTITUDE-CONTROLLED TEST PLATFORMS

by Norman M. Hatcher and Richard N. Young

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AN AUTOMATIC BALANCING SYSTEM FOR USE ON FRICTIONLESSLY SUPPORTED ATTITUDE-CONTROLLED TEST PLATFORMS

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SUMMARY

An automatic balancing system for frictionlessly supported, attitude-controlled test platforms about axes that are commonly orthogonal to the gravity vector is discussed. The system determines imbalance during limit-cycle operation by measuring the difference in total impulse exerted by opposing torquers that are used for attitude control in each axis to be balanced during some time interval. The system then moves a small weight by an appropriate distance to compensate for the measured imbalance.

A model of the automatic balancing system has been constructed and tested on an air-bearing-supported platform that was fitted with sun sensors and a reaction-jet attitude-control system. Results indicated that the automatic balancing system can consistently balance this platform more accurately than it can be balanced manually, and that it can maintain this balance throughout prolonged test periods. The average accuracy to which the system balanced the platform during the tests was approximately 3000 dyne-cm. The system is compatible with present-day attitude-control systems, requires little power, and can be made small in weight and volume.

INTRODUCTION

In developing and preflight testing spacecraft attitude sensors, attitude-control (torquing) systems, and other spacecraft components, it is often necessary to test these components under simulated space-flight conditions on air-bearing-supported, attitude-controlled platforms. For these applications the platforms must be balanced to the best possible extent; that is, to within a few thousand dyne-cm. Any imbalance can increase control-fuel usage or power consumption, decrease orientation accuracy, and increase the time initially required for the system to orient the platform.

Currently, most air-bearing-supported platforms are balanced manually. However, balancing a platform manually is undesirable because the balancing process is time consuming and limited in accuracy. One balancing system has been reported (by Felix Zajac and David Small of Goddard Space Flight Center in 1963) that derives imbalance information prior to a test by sensing the angular acceleration of the platform about its control axes. Neither this system nor the manual-balancing techniques can maintain the balance of a platform while a test is in progress. For tests of more than a few minutes, the platform may have to be rebalanced periodically to compensate for center-of-gravity shifts. These shifts can be caused by anisoelasticity (deflections of platform components due to gravity); unequal expansion of components resulting from variations in temperature; component shifts due to necessary clearances between gears, bearings, and other devices; movements of such items as leads, which are not securely tied down; and unsymmetrical fuel usage with respect to the center of support. Compensation may also be made for the torquing effects of wire leads to the platform, air-bearing torques, and room air currents, for they may not vary appreciably with time. Thus, the need for a completely automatic balancing system is apparent.

Desirable features of such a system are accuracy, reliability, fast response, compatibility with all vehicular torquing systems, ability to operate within a wide range of imbalances, and low weight, volume, and power consumption. Either of several automatic balancing techniques might be used which would approximate these conditions. For example, accelerometers might be used to measure differences in platform acceleration during either the on-time or the off-time of opposing torquers about each control axis. This difference in acceleration should be proportional to the imbalance moment. A second possible technique would use control-gas storage tanks located on opposite sides of each control axis, each tank supplying one of the opposing thrusters. This simple concept would automatically compensate for imbalance by reducing the control-gas weight on the heavier side. It would, however, be useful only with mass-expulsion control systems.

Still another automatic balancing technique, which is the subject of this report, determines platform imbalance during limit-cycle operation by measuring, during a preset period of time, the difference in total impulse exerted by opposing torquers in each control axis. The system then displaces a small balance weight in the proper direction by a distance which will null this imbalance. Under ideal conditions, the net impulse is directly proportional to the imbalance torque (fig. 1). This concept has been developed and tested on a typical air-bearing-supported platform. The principles of operation, the mechanical and electronic design, the theoretical performance, and the measured performance of this automatic balancing system (ABS) are discussed.

SYMBOLS

C	feedback capacitance, farads
E	input voltage to automatic balancing system, volts

E_d integrator discharge voltage, volts

I inertia of test platform about axis to be balanced, slug-feet^2 (gram-centimeters^2)

k_1 setting of input potentiometer R_1

k_2 setting of discharge potentiometer R_2

L^+ torque in positive direction, dyne-centimeters

L^- torque in negative direction, dyne-centimeters

$L_{control}$ control torque, dyne-centimeters

$L_{imbalance}$ imbalance torque, dyne-centimeters

$L_{imbalance,max}$ maximum imbalance that must be corrected for in any single balance-sampling period, dyne-centimeters

L_ϵ maximum error in automatic balancing system due to differences in angular velocity of platform at t_o and t_e, dyne-centimeters

m mass of actuator, grams

R equivalent resistance, R_1'/k_1, ohms

R_1' resistance of input resistor to integrator, ohms

R_2' resistance of input resistor in discharge circuit, ohms

T^+ total on-time of positive torquer, seconds

T^- total on-time of negative torquer, seconds

t balance-sampling period, seconds

t_e end of balance-sampling period, seconds

t_o	beginning of balance-sampling period, seconds
$\|\Delta t\|$	maximum on-time of torquers during one excursion, seconds
V	voltage, volts
V_{max}	maximum integrated output voltage, volts
V_o	initial voltage, volts
v	translation rate of balance mass, grams/centimeter-second
θ	pointing error of test platform, radians
$\dot{\theta}$	angular velocity of test platform, radians/second
$\ddot{\theta}$	angular acceleration of test platform, radians/second^2

Notations used for devices in circuitry:

C	feedback capacitor
$\left.\begin{matrix} D_1, D_2 \\ D_3, D_4 \end{matrix}\right\}$	diodes
Q_1, Q_2	transistors used in relay-drive circuit
$\left.\begin{matrix} Q_3, Q_4 \\ Q_5, Q_6 \end{matrix}\right\}$	transistors used in integrator-discharge circuit
R_1	input potentiometer
R_2	discharge potentiometer

PRINCIPLES OF OPERATION

Basic Operating Principles

The basic operating principle of the automatic balancing system (ABS) is illustrated in figure 1. The net impulse exerted by the opposing torquers about each control axis during a balance-sampling period t is $\int_{t_o}^{t_e} L_{control}\, dt$. By assuming that the angular velocities of the platform at t_o and t_e are equal and in the same direction and that no external perturbing torques are present,

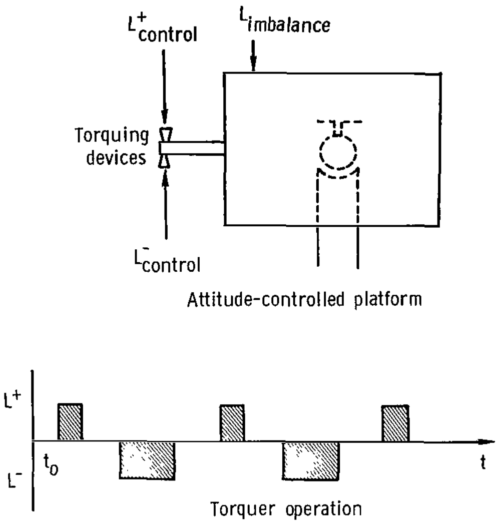

Figure 1.- Basic operating principles of automatic balancing system (ABS).

$$L_{imbalance} = \frac{\int_{t_o}^{t_e} L^+_{control}\, dt - \int_{t_o}^{t_e} L^-_{control}\, dt}{t} \tag{1}$$

where superscripts + and - denote opposing torque directions. The $L_{imbalance}$ is measured by utilizing the torquer driving signals, produced by the attitude sensors, to charge feedback capacitor C (fig. 2) positively during the on-time of the L^+ torquer and negatively during the on-time of the L^- torquer. The net voltage V on capacitor C after a time t is proportional to $L_{imbalance}$, and the polarity of the charge indicates the direction of $L_{imbalance}$. The timer will, after the interval t, activate a relay which applies the voltage on capacitor C to the operational amplifier 2. The purpose of this

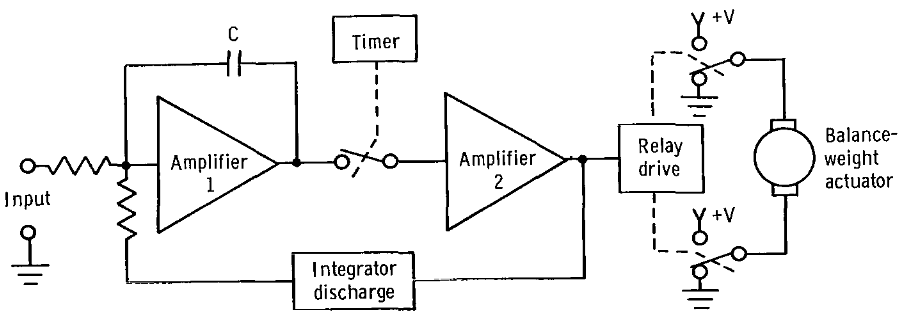

Figure 2.- Block diagram of ABS.

amplifier is to increase the sensitivity of the ABS as well as to act as a buffer. When the output of amplifier 2 is not zero, the integrator discharge circuit feeds a signal back to the integrator, discharging the capacitor linearly at a preset rate. Amplifier 2 also actuates the relay-drive circuit, energizing one of the relays and thus operating the balance-weight actuator motor. The duration of motor operation is controlled by the discharge rate and by the voltage on capacitor C at the end of the balance-sampling period.

In the ABS test model, the input signals were derived directly from the signals driving the reaction-jet solenoids. In proportional control systems, the summed rate plus error signal is often available and is used directly to control the direction and magnitude of the control torque. Thus, it is this signal which would be processed by the ABS.

Circuit Functions

Figure 3 shows a schematic diagram of the electronic circuit for the ABS. Operational amplifier 1, capacitor C, and the 1-megohm input resistor form the analog-integration circuit. This circuit performs the following integration process (ref. 1):

$$V = V_o - \frac{1}{RC}\int_{t_o}^{t_e} E\,dt \tag{2}$$

where E is proportional to the torque level, torquer on-time, and torque polarity. The initial voltage V_o is set equal to zero.

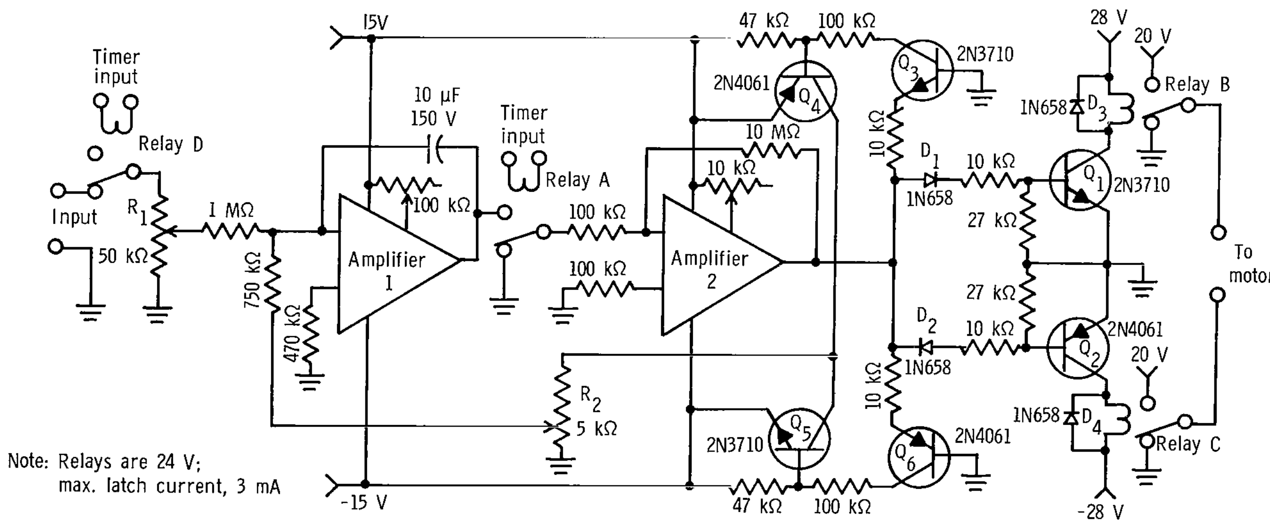

Figure 3.- Schematic diagram of electronic circuit for ABS.

In control systems for which the torque level is constant but varies in the on-time (reaction-jet systems, for example),

$$V = -\frac{E}{RC}(T^{+} - T^{-}) \tag{3}$$

The gain of this circuit is made compatible with the input-signal amplitude by adjusting potentiometer R_1.

Since the electronic circuit only records the net impulse exerted by the torquers during t, either or both $L_{control}$ and torquer on-time may be fixed or variable without modifications to the ABS. The output of the integrator is fed through a timer-controlled relay to operational amplifier 2. The primary purpose of amplifier 2 is to increase the sensitivity of the ABS by holding the output of the integrator at a sufficiently high level to maintain conduction of transistor Q_1 or Q_2 until capacitor C is almost fully discharged. The polarity of the output determines whether conduction of transistor Q_1 or Q_2 is maintained. Thus, amplifier 2 operates in saturation part of the time. (The gain of amplifier 2 was set at 100 in the present ABS model circuitry.) Amplifier 2 drives two separate citcuits: the relay-drive circuit, consisting of transistors Q_1 and Q_2; and the integrator-discharge circuit, consisting of transistors Q_3, Q_4, Q_5, and Q_6. Diodes D_1 and D_2 hold the sensitivity of the relay-drive circuit below that of the integrator-discharge circuit so that the weight actuating motor will turn off before the integrator ceases to discharge. The discharge rate is made compatible with factors such as motor speed, gear ratios, and balance-weight mass by adjusting potentiometer R_2. Equations for the settings of potentiometers R_1 and R_2 are derived in appendix A.

Measured total power consumption of the electronic circuit of the model was 2.04 watts during the balance-sampling period. The solid-state timer used 0.44 watt.

Weight Actuator

The weight actuator used in the ABS test model consists of a direct-current motor driving a threaded shaft which, in turn, moves a weight along the axis of the shaft. Since the motor is operated from a voltage-regulated power supply and drives a relatively small load, its operation is at an essentially constant speed in one direction or the other, depending upon the polarity of the integrator output. Because the integrator is discharged at a constant rate, the operating time of the motor is directly proportional to the voltage that has been built up on the capacitor during the balance-sampling period.

The weight actuator, shown in figure 4, has a rotor speed of 12 000 rpm and is geared to drive the threaded shaft at 200 rpm. A screw is attached to the balance weight so that additional mass can be added. The motor applies equal and opposite impulses to the platform during starting and stopping. These impulses could be detrimental for certain tests during which the platform acceleration and/or orientation error must be

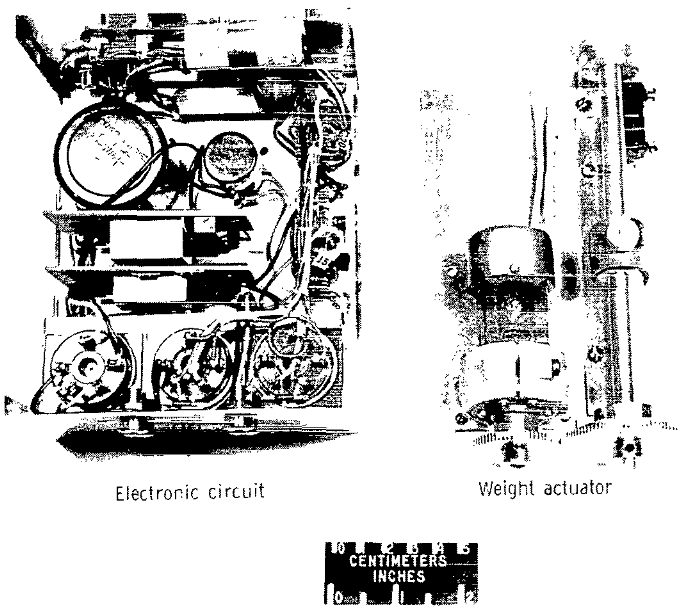

Figure 4.- ABS test model. L-67-2953.1

kept extremely low. If necessary, these impulses could be essentially eliminated by using, for example, a small stepping motor in place of the dc motor. The motor used in the ABS test model produced torque impulses of approximately 11 000 dyne-cm-sec, with no detected effect upon the test platform.

The motor used 4.2 watts during the short time it operated. Weight of the ABS test model, which consisted of the electronic circuit and the balance-weight actuator, was 4.3 lbm (1.95 kg). However, this has been reduced in a later model to 2.8 lbm (1.27 kg) by using smaller relays and by mounting both the weight actuator and the electronic circuit in a single box, as shown in figure 5. The volume and average power consumption of this reduced model are approximately 85 in^3 (1400 cm^3) and 2.5 watts, respectively, for each axis of operation. Location of the ABS on the platform is unimportant, although the weight actuator must be properly oriented with respect to the axis about which it maintains balance.

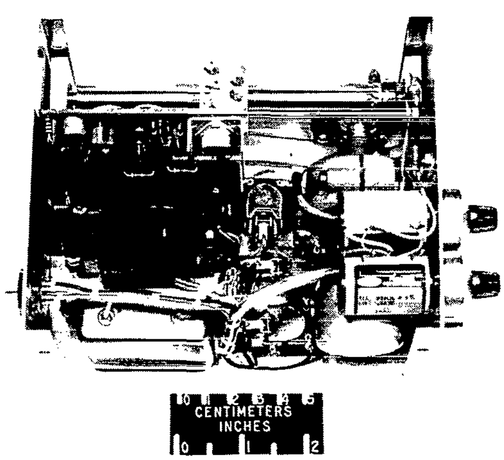

Figure 5.- ABS with weight actuator and electronic circuit in a single box.

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Accuracy

Several factors exist that might limit the accuracy of the ABS. These factors are as follows:

(1) Deviations in balance-sampling time

(2) Lags in the balance-weight actuating mechanism

(3) Capacitor leakage

(4) Other mechanical and circuitry imperfections

(5) Differences in response time and torque levels of reaction-jet control systems

(6) Perturbing forces other than the imbalance moment

(7) Differences in angular velocity at t_o and at t_e.

Experimentation has shown that factors (1) to (4) can be reduced to nearly insignificant levels by carefully selecting and machining components of the ABS. Factor (5) would not normally be a significant error source, since differences in response time of the reaction jets, due to valve inertia, are only a few milliseconds or less. Also, any differences in torque levels of opposing torquers could be readily compensated for by incorporating a dual input to the ABS with separate potentiometers for adjusting the gain of each input. Factor (6) will normally be caused only by air-bearing torques, room air currents, and torques due to wire leads to the platform. With care, torques due to wire leads and room air currents can usually be reduced to inconsequential levels. Air-bearing torques often do not vary appreciably, in direction, with time and should, in this instance, be compensated for in the same manner as imbalance moments. Factor (7) could significantly reduce the accuracy of the ABS under the simultaneous conditions that t must be kept short and angular velocity is high. This factor is examined in appendix B.

PERFORMANCE TESTS

Performance tests were conducted on an air-bearing-supported platform (fig. 6) to get an indication of the accuracy of the ABS as a function of imbalance magnitude, balance-sampling period, control-torque level, and differences in angular velocity at the beginning and at the end of the balance-sampling period. The imbalance magnitude was varied between 20 000 dyne-cm and 100 000 dyne-cm, and the balance-sampling period was varied between 0.5 minute and 8 minutes. The control-torque levels used were 56 000 dyne-cm, 113 000 dyne-cm, and 260 000 dyne-cm. Since the operation of the ABS is identical for each axis, only a single-axis system was constructed and investigated. Prior to conducting the tests, room air currents were minimized by all available means,

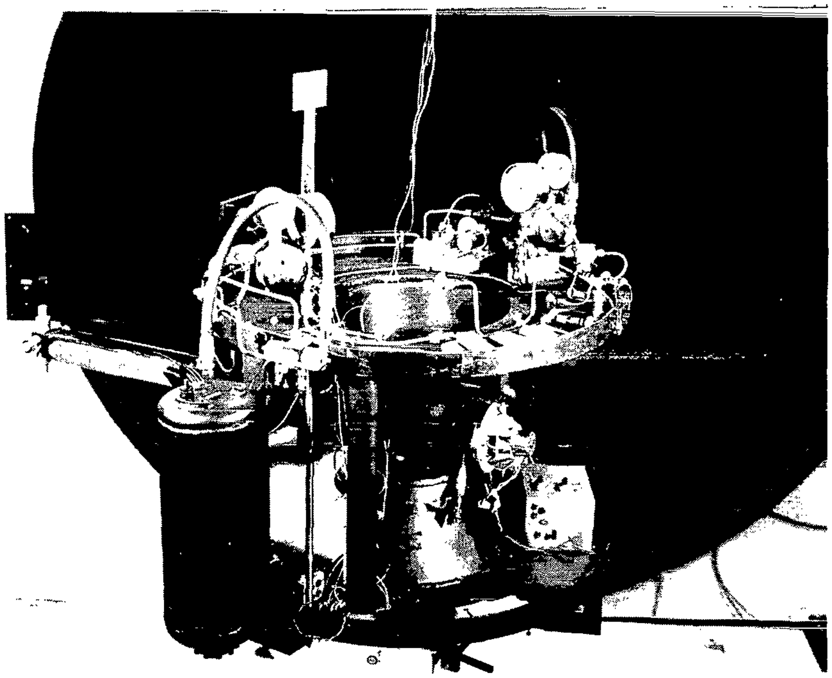


Figure 6.- Test platform used in evaluating ABS. L-67-2951

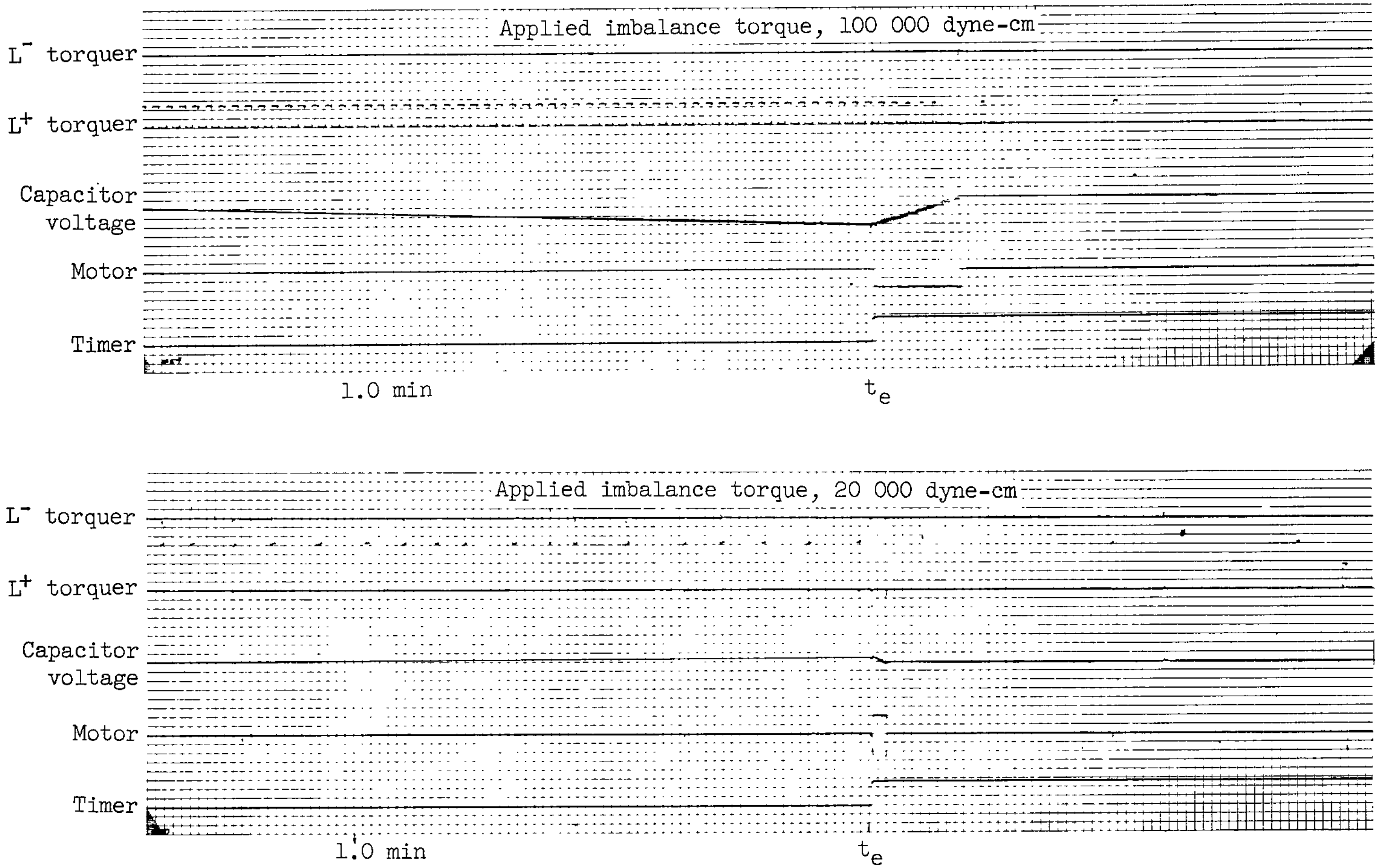
although some residual air currents were present. The platform was then balanced manually in three axes to an accuracy of better than 10 000 dyne-cm. Sun sensors and a simulated solar-radiation source were used to provide attitude reference signals.

RESULTS AND DISCUSSION

Preliminary studies showed that the ABS could balance the platform more accurately than it could be balanced manually. Thus, the ABS was allowed to minimize platform imbalance prior to each test.

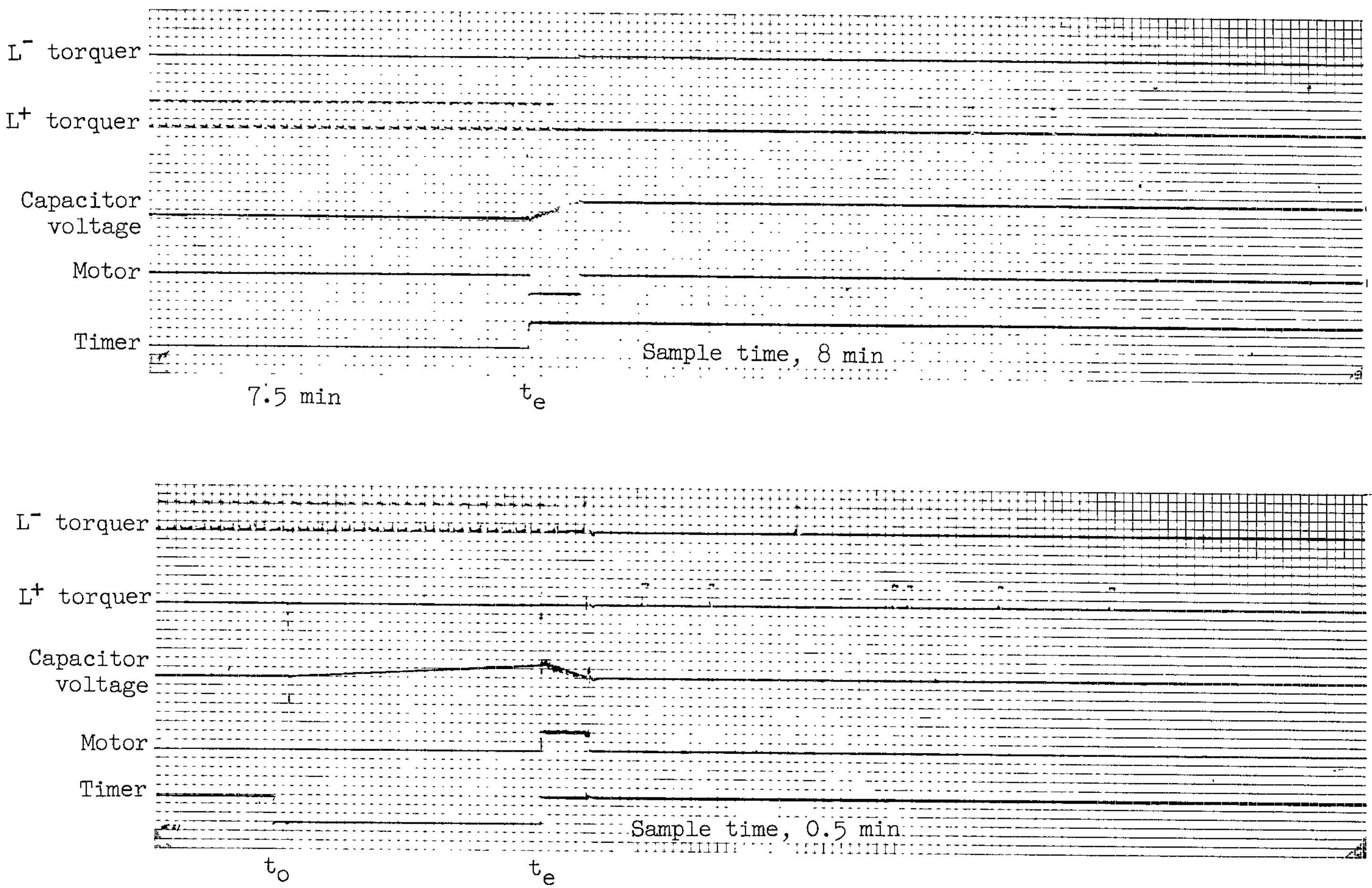
Figures 7(a), (b), and (c) show typical recordings of key parameters by indicating the operation of the ABS as a function of different applied imbalance torques, balance-sampling periods, and control torques, respectively. Figure 7(d) illustrates the effect of relatively large differences in angular velocity at the beginning and at the end of the balance-sampling period. This factor is discussed in appendix B. Figure 7(e) shows excerpts from a record of a continuous 68-minute test run during which the ABS was required to maintain the balance of the test platform.

The studies indicated that, for the conditions existing during the tests, accuracy of the ABS increased somewhat with balance-sampling period, although accuracy did not increase significantly for sample times longer than 2 minutes. Accuracy decreased



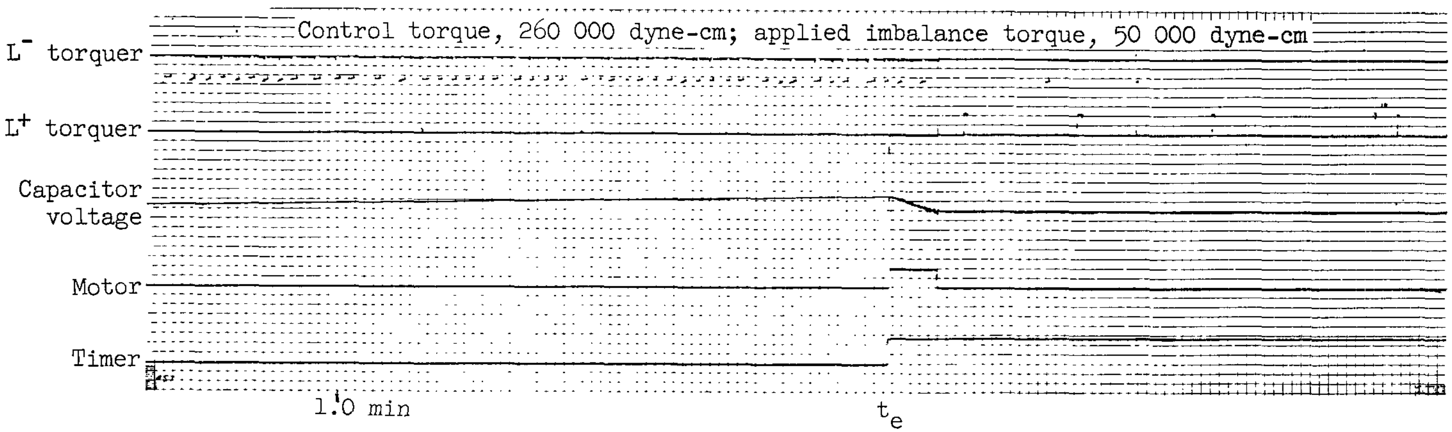
(a) Operation with different imbalance torques. Balance-sampling period, 2 minutes; control torque, 113 000 dyne-cm.

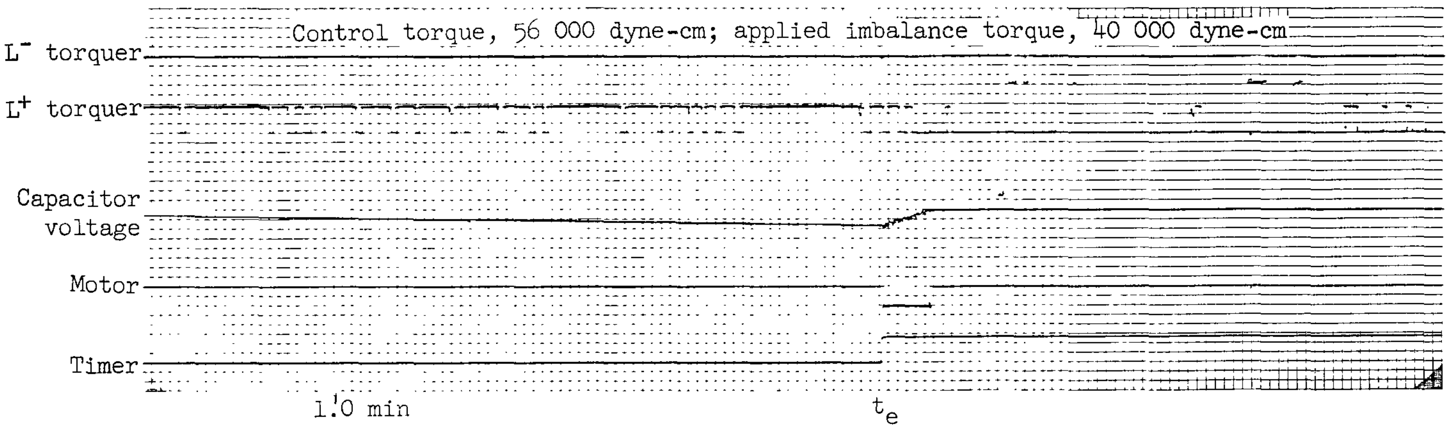
Figure 7.- Recordings of ABS operation during dynamic tests.



(b) Operation with different balance-sampling periods. Applied imbalance torque, 50 000 dyne-cm; control torque, 113 000 dyne-cm.

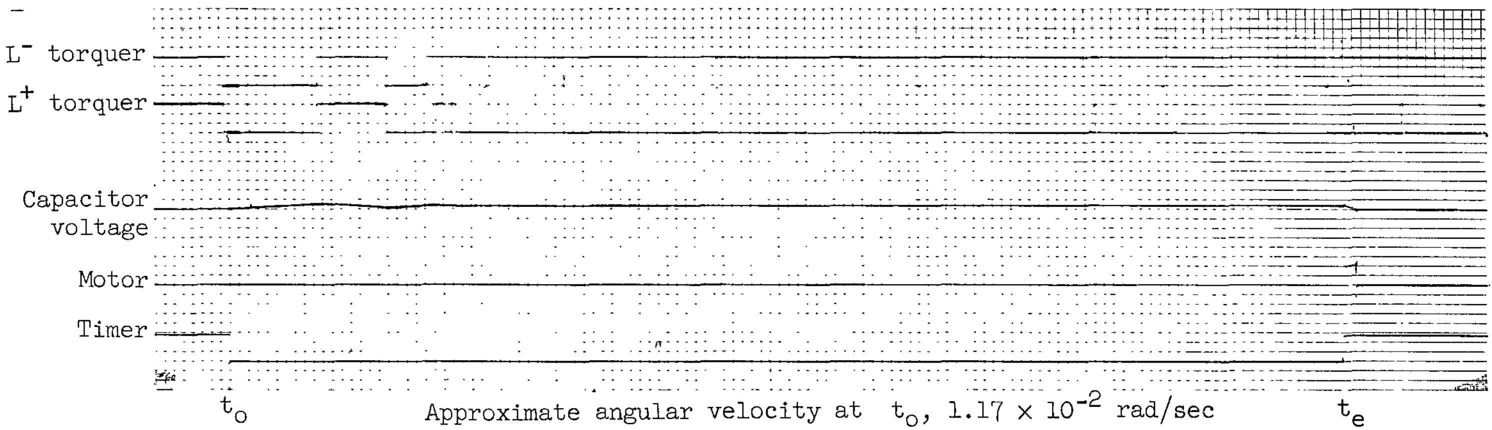
Figure 7.- Continued.





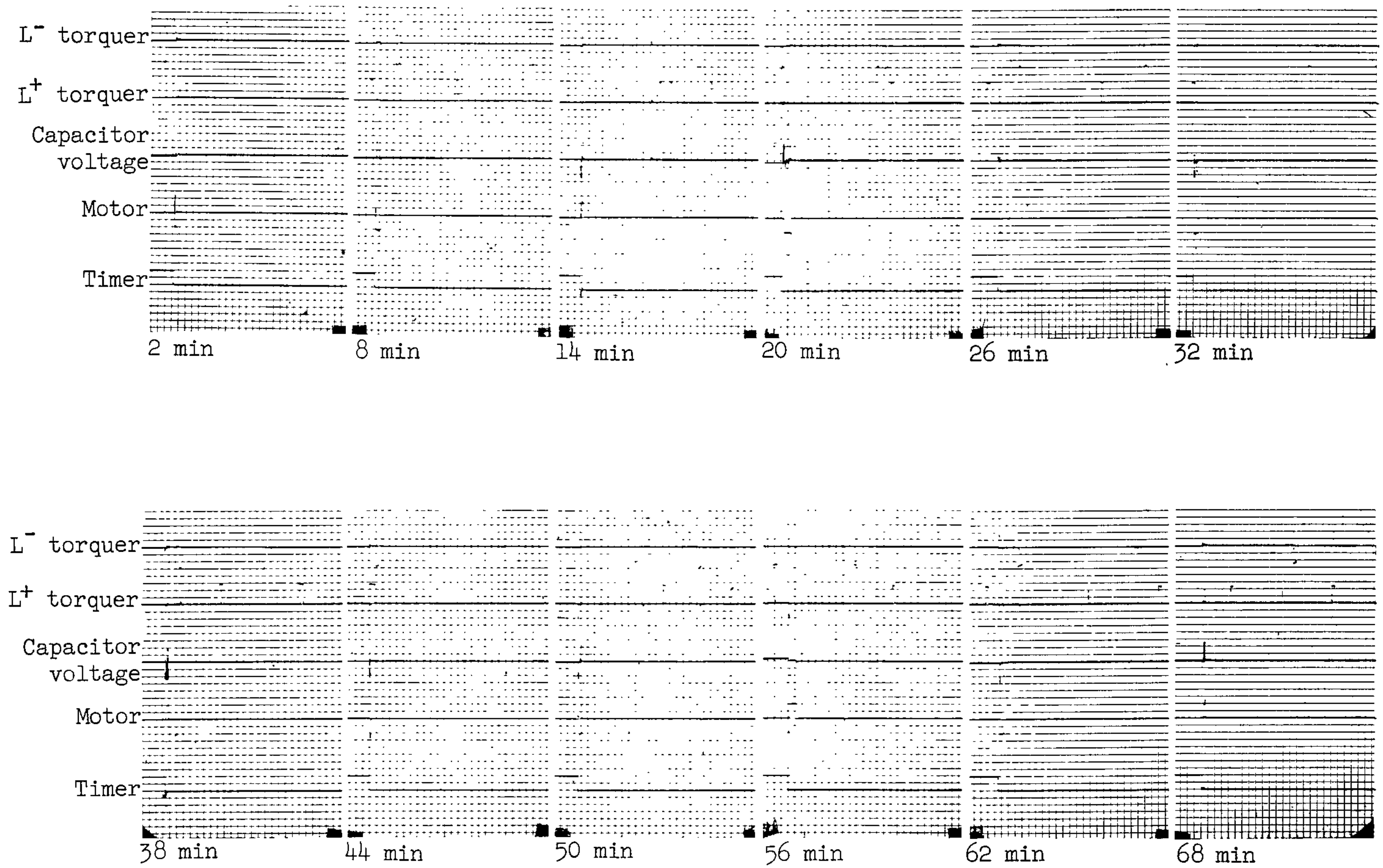
(c) Operation with different control torques. Balance-sampling period, 2 minutes.

Figure 7.- Continued.



(d) Operation with applied angular velocity at beginning of balance-sampling period. Balance-sampling period, 2 minutes; applied imbalance torque, none; control torque, 260 000 dyne-cm.

Figure 7.- Continued.



(e) Operation during long-term test. Balance-sampling period, 2 minutes; inactive period, 4 minutes; control torque, ±113 000 dyne-cm.

Figure 7.- Concluded.

slightly as control torque was increased, probably due to increasing differences in angular velocity at t_o and at t_e. The accuracy was apparently independent of initial imbalance within the range of imbalances that were applied. Relatively large differences in angular velocity at the beginning and at the end of short balance-sampling periods produced appreciable errors in the ABS, as shown in figure 7(d).

An analysis of the complete recording of the 68-minute test run indicated that appreciable varying external torques, probably due to room air currents, were present. These torques were interpreted as imbalance torques by the ABS, which made center-of-gravity compensations that were equivalent to motor on-times of as much as 1 second (1 second of motor operation shifted the center of gravity by 9000 dyne-cm). The average measured error of the ABS was deduced, during 20 test runs, from the measured difference in recorded on-times of opposing jets after the balance-sampling period. This error was approximately 3000 dyne-cm. However, the exact error could not be determined since the recordings could probably not be read to accuracies better than 1000 dyne-cm. The maximum measured error for any test was approximately 10 000 dyne-cm and was due to the influence of room air currents.

CONCLUSIONS

An automatic balancing system for frictionlessly supported, attitude-controlled platforms has been designed, constructed, and tested on an air-bearing-supported platform. Although only a reaction-jet attitude-control system was used in the studies, it should be possible to make the automatic balancing system compatible with all spacecraft control systems. Within the scope of the studies, the following conclusions were drawn regarding the performance of the automatic balancing system:

1. The system could initially balance air-bearing-supported platforms more accurately than they could be balanced manually and it could maintain the balance of the platform for prolonged periods of time. The average measured error of the automatic balancing system during the tests was approximately 3000 dyne-cm.

2. Balance accuracy was essentially independent of the magnitude of constant imbalance torques.

3. Balance accuracy increased with balance-sampling period, although reasonably good accuracies were achieved with balance-sampling periods of as little as 0.5 minute.

4. Balance accuracy increased with decreasing control torque.

5. Balance accuracy decreased with increasing differences in angular velocity of the platform at the beginning and at the end of the balance-sampling period. Under ideal

test conditions, this effect was the only significant factor limiting the accuracy of the system.

6. Weight, volume, and average power consumption were approximately 2.8 lbm (1.27 kg), 85 in^3 (1400 cm^3), and 2.5 watts, respectively, for each axis of operation.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., September 27, 1967,
125-19-03-09-23.

APPENDIX A

DERIVATION OF EQUATIONS FOR POTENTIOMETERS R_1 AND R_2 SETTINGS

As mentioned under "Basic Operating Principles," potentiometers R_1 and R_2 must be adjusted to make the gain compatible with several ABS circuitry and control-system parameters. If these parameters are known, potentiometers R_1 and R_2 can be properly set according to the expressions which are derived in this section.

The setting of potentiometer R_1, which is used to make the gain of the integrator compatible with the input voltage, is found in the following manner:

Integrating equation (1) given previously yields

$$L_{imbalance} = \frac{L_{control}(T^{+} - T^{-})}{t} \tag{A1}$$

Rewriting equation (3) gives

$$V = \frac{-E(T^{+} - T^{-})}{RC} \tag{A2}$$

Rewriting equations (A1) and (A2) gives

$$(T^{+} - T^{-}) = \frac{L_{imbalance}(t)}{L_{control}} \tag{A3}$$

$$(T^{+} - T^{-}) = -\frac{VRC}{E} \tag{A4}$$

By equating the total integrated torquer on-time appearing in equations (A3) and (A4), the following form is obtained:

$$\frac{1}{RC} = \frac{-VL_{control}}{EL_{imbalance}(t)} \tag{A5}$$

However, R is actually a composite term consisting of R_1'/k_1. Thus,

$$\frac{k_1}{R_1'C} = \frac{-VL_{control}}{EL_{imbalance}(t)} \tag{A6}$$

Solving for k_1 (the setting of R_1) yields

$$k_1 = -\left(\frac{V}{L_{imbalance}}\right)\left(\frac{L_{control}}{E}\right)\frac{R_1'C}{(t)} \tag{A7}$$

The term $\left(\frac{V}{L_{imbalance}}\right)$ in equation (A7) is the output of the ABS in volts per unit of imbalance. In order to obtain the maximum usable dynamic range of imbalance correction, the maximum integrator-output voltage before saturation is substituted for V and the maximum imbalance for which the ABS is expected to have to correct for after any one balance-sampling period is substituted for $L_{imbalance}$. During the performance studies discussed previously, the maximum $L_{imbalance}$ was assumed to be 100 000 dyne-cm. The term $\left(\frac{L_{control}}{E}\right)$ is the input to the ABS by the attitude control system (dyne-cm/volt). This factor is often convenient because proportional control systems usually have a voltage present where this ratio is known or can easily be determined.

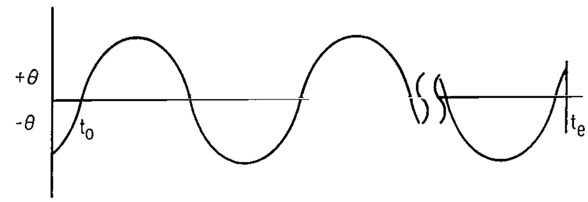
Potentiometer R_2 is associated with the weight movement and integrator discharge circuit. The derivation for the setting of potentiometer R_2 is very similar to that of equation (A7). The result, in terms of electrical and mechanical quantities, is

$$k_2 = -\left(\frac{V_{max}}{L_{imbalance,max}}\right)\left(\frac{mv}{E_d}\right)R_2'C \tag{A8}$$

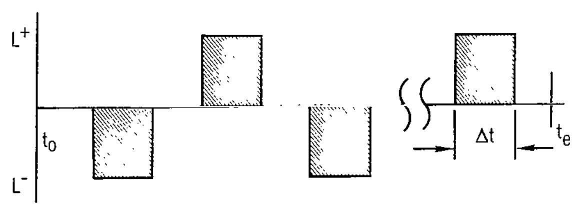
APPENDIX B

EFFECT OF ANGULAR VELOCITY ON ACCURACY OF AUTOMATIC BALANCING SYSTEM

For equation (1) to be valid, the angular velocities of the platform at t_o and t_e must be equal and in the same direction. Figure 8 shows graphically how errors in the ABS can occur if this condition is not met. It is apparent from the figure that the maximum error L_ϵ in force-distance units will occur when the number of positive and negative excursions from zero pointing error, sampled during t, differ by one full excursion. For this investigation,



Angular motion of platform about one axis



Torquer operation

Figure 8.- Possible error in ABS due to different angular velocities of platform at beginning and at end of balance-sampling period.

$$L_\epsilon = \frac{L_{control}\Delta t}{t} \tag{B1}$$

In order to determine the approximate magnitude of L_ϵ, exclusive of measuring Δt under operating conditions, an expression relating Δt to other characteristics of the platform and of the control system is obtained as follows:

Since the maximum angular excursion is

$$\theta = \frac{1}{2}\ddot{\theta}\left(\frac{\Delta t}{2}\right)^2$$

where

$$\ddot{\theta} = \frac{L_{control}}{I}$$

then

$$\Delta t = 2\sqrt{\frac{2\theta I}{L_{control}}} \times \text{Duty cycle} \tag{B2}$$

where duty cycle is the ratio of the torquer on-time to the torquer period.

Substituting equation (B2) into equation (B1) gives

$$L_{\epsilon} = 2\,\frac{\sqrt{2\theta I L_{control}}}{t} \times \text{Duty cycle} \tag{B3}$$

Thus, L_{ϵ} is directly proportional to I, since $L_{control}$ must vary in direct proportion to I if θ, t, and duty cycle are held constant.

In order to determine experimentally the effects of relatively large angular excursions on the accuracy of the ABS, the balanced platform was offset by an angle of 2° (0.035 radian) and released. The orientation system accelerated the platform toward zero pointing error and the balance-sampling period of the ABS was started at approximately 0.5° (0.0087 radian). Here the opposite control jet was turned on by action of the rate system to provide damping (fig. 7(d)). Thus, the effective offset angle θ was approximately 1.5° (0.026 radian) for an effective duty cycle of 100 percent with a control torque ($L_{control}$) of 113 000 dyne-cm. Substituting these values into equation (B3) and multiplying by 0.5 to simulate a $\dot{\theta}$ at t_e which is equal to that value at t_o but opposite in direction yields a value for L_{ϵ} of 9600 dyne-cm. (The value of I_{pitch} of the test platform was approximately 7.3 slug-ft^2 (9.9×10^7 g-cm^2).) By considering the limitations in the accuracy to which the recording could be read, this value is in reasonable agreement with the measured value for L_{ϵ} of approximately 11 000 dyne-cm. For most tests, angular velocity differences of this magnitude will probably not be encountered. If such differences are expected, however, the balance-sampling period, perhaps, should be extended beyond 2 minutes. If the balance-sampling period must also be kept short, L_{ϵ} could be minimized by one of several means. For example, a small light source could be provided in conjunction with platform-mounted photosensors and logic circuitry to initiate and terminate the balance-sampling period at the same angular velocity.

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